Comparison of Head-Up and Head-Down "Highway-In-The-Sky" Tunnel And Guidance Concepts For Synthetic Vision Displays

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Two experiments are discussed that compared different tunnel and guidance symbology concepts for advanced aviation displays, such as synthetic vision display systems. These experiments used synthetic vision head-down and head-up displays and evaluated the efficacy of these concepts during complex, curved visual arrival approaches under CAT I instrument meteorological conditions. The results of these two experiments are described and implications for design of advanced aviation displays are discussed.

INTRODUCTION

Synthetic vision is a display system that presents a view of the outside world to the flight crew by melding computer-generated scenes from on-board databases and flight display symbologies, with information derived from weather-penetrating sensors (e.g., object detection algorithms) or actual imagery from on-board sensors (e.g., forward-looking infrared) that augment the database imagery to provide enhanced integrity. Synthetic Vision Systems (SVS) are characterized by the ability to represent visual information and cues intuitive to that experienced during daylight, visual meteorological conditions (VMC). In terms of safety benefits, synthetic vision may help to reduce many accident precursors including (Parrish, Baize, & Lewis, 2001):

- Loss of vertical and lateral spatial awareness
- Loss of terrain and traffic awareness on approach
- Unclear escape or go-around path even after recognition of problem
- Loss of altitude awareness
- Loss of situation awareness relating to the runway environment and incursions
- Unclear path guidance on the surface

The NASA synthetic vision system will integrate synthetic vision head-down, head-up, helmet-mounted, and navigation displays; runway incursion prevention technologies; database integrity monitoring equipment; enhanced vision sensors; taxi navigation displays; "highway-in-the-sky" tunnels and guidance; and advanced communication, navigation, and surveillance technologies.

To date, research has successfully demonstrated both the safety and capacity benefits of SVS. Research has also focused on significant human factors research (e.g., Prinzel et al., 2002; 2003; 2004). The present paper reports on two such experiments that examined the efficacy of pathway/tunnel concepts that may be integrated as part of future synthetic vision primary flight and head-up displays (HUDs).

Research Objective

Experiment One focused on the SVS primary flight display (PFD) and examined four tunnel concepts ("minimal", "full" or "box", "dynamic pathway", "dynamic crow's feet") and three guidance symbologies ("ball", "tadpole", "ghost") during approaches to Reno, NV airport (RNO) using the Sparks 16R Visual Arrival under CAT IIIb instrument meteorological conditions (IMC). Based on the results from Experiment One, Experiment Two evaluated two pathway ("minimal", "dynamic crow's feet") and two guidance ("tadpole", "ghost") concepts for a synthetic vision HUD using the same scenarios as Experiment One. In addition, a "rare-event" runway incursion scenario was also presented.

EXPERIMENT ONE

Pilot Participants

Eight commercial pilots, who fly for major commercial airlines, participated in the experiment. All participants were HUD-qualified and were rated B-757 Captains. The HUD requirement was to ensure familiarity with a velocity vector and guidance symbology. All participants also had logged flight time in "glass cockpits" (e.g., A-320; MD-11) other than the B-757; therefore, all participants were familiar with a primary flight display (PFD).

Tunnel Concepts

Four tunnel (box, minimal, dynamic "crow's feet", dynamic pathway) concepts and a baseline (no tunnel) configuration were evaluated (see Figure 1). The "box" tunnel, a concept that is the subject of most of the tunnel research in the literature, consisted of a series of connected rectangles at the corners of the vertical and lateral path within which the pilot should fly. It was presented out to a length of 10 nm, with no fading. The minimal tunnel concept consisted of a series of "crows feet" presented in each corner of a tunnel segment (essentially a truncated box). The tunnel was drawn with 5 tunnel segments per nautical mile (nm) with a total length of 3 nm, and faded gradually to invisibility over the last nautical mile. The third concept, dynamic "crows feet", allowed the "crows feet" to grow as a function of path error. Therefore, the pilots are given feedback as to where they are in the tunnel and if they are close to flying out of the tunnel. The idea of the dynamic tunnel was that if the pilot is flying in the center of the tunnel, there should be the smallest amount of clutter. However, if there exists appreciable path error, the tunnel walls would "grow" to help the pilot gauge where the boundaries of the tunnel are. This helps to overcome a frequent criticism of "low clutter" tunnels. The fourth concept, dynamic pathway, was a variation of the dynamic "crow's feet" concept in which the floor of the tunnel was presented at all times. For both the dynamic pathway and dynamic "crow's feet", when the pilot left the tunnel, the tunnel would change to a "trough" and resemble a box tunnel with the exception that the tunnel would open to "invite" the pilot back into the tunnel. All concepts and the baseline were paired with a navigation display with a Terrain Awareness Warning System (TAWS).

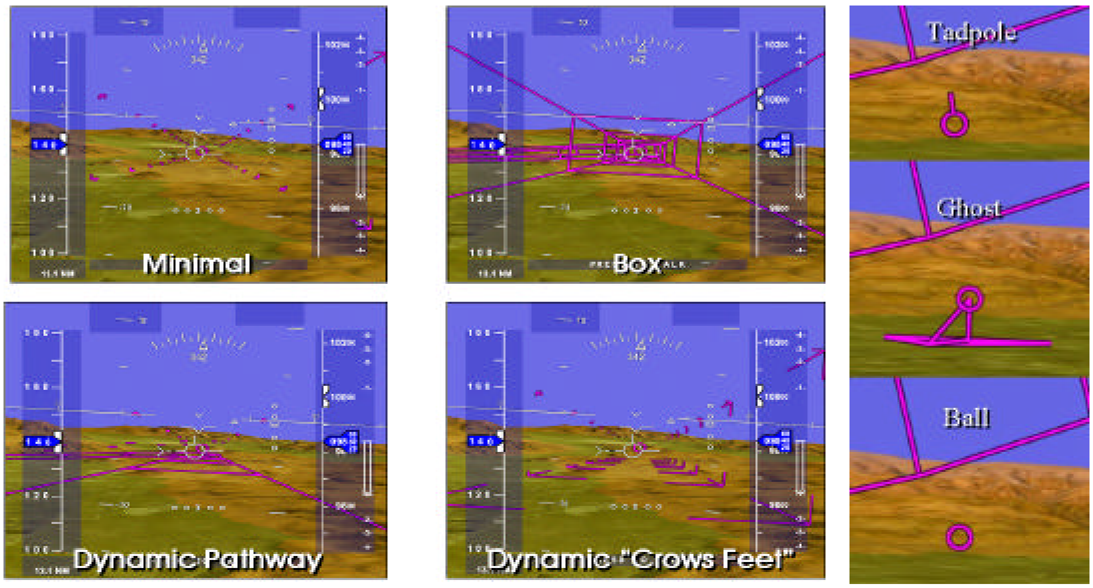

Figure 1. Four Tunnel & Three Guidance Concepts

Guidance Concepts

The guidance concepts were either an integrated cue circle ("ball") used in several HUDs, a "follow-me" aircraft concept ("ghost"), or a "tadpole" guidance symbol. The integrated cue circle symbol was the tail-light portion of the ghost symbol positioned 30-seconds ahead of ownship on the centerline of the tunnel. Yaw, pitch, and roll attitude of the ghost reflected the track and flight path angles of the path at that lead position. The tadpole provided similar information to the integrated cue with added track change information provided by the winglet on the ball cue. The tadpole symbology is used in some military aircraft HUDs (e.g., F-16).

Experimental Task

The evaluation task was the Sparks Visual Arrival to Runway 16R at Reno airport (RNO). Twenty-two experimental runs were completed during the experimental session. The runs differed by the (1) initial starting position outside the tunnel, (2) the guidance symbology, and (3) task scenario. There were three initial starting positions that were randomly varied across trials to force the pilot to re-enter the tunnel on each run. The guidance symbology was also randomly assigned and factorially combined with the four tunnel concepts. Finally, there were two scenarios required of the pilot participants. The first was the nominal Sparks 16R Visual Approach, but flown under IMC, and the second was a "cut-the-corner" scenario in which the pilot was instructed by simulated Air Traffic Control (ATC) to fly "direct to" a waypoint on the final approach segment which required the pilot to leave the tunnel path and then re-enter. The latter scenario required the pilot to utilize the navigation display (i.e., using the track predictor symbol to acquire the heading) and later to use the guidance symbology and velocity vector to re-enter the tunnel.

Simulation Facility

The experiment was conducted in the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III pilot workstation at NASA Langley Research Center. The single pilot fixed based simulator consists of a 144° by 30° Out-The-Window (OTW) scene, a large field head-down display (HDD) and pilot input controls. The OTW scene was used only during training. The pilot controls in the VISTAS III workstation are a left side arm controller, left/right throttle controls, rudder pedals, toe brakes, a PC track ball for display-related pilot inputs, and a voice recognition system (VRS). The aircraft model was a B-757, and the approach speed was 138 knots. All scenarios were flown with moderate turbulence. Auto throttles were used, flaps were set to 30 degrees, and the landing gear was down.

Results

After each run, pilots were administered a run questionnaire consisting of the USAF Revised Workload Estimation Scale, Situation Awareness Rating Technique (SART), and six Likert-type (7-point) questions specific to tunnel and guidance symbology evaluation. A SA-SWORD and semi-structured interview were also administered. The post-run and semi-structured interview results are not discussed here, but they generally support the results of the other dependent variables.

Flight Path Control

Flight path control was analyzed for the nominal task run for root-mean-squared error (RMSE). An ANOVA found a significant effect for lateral RMSE, $F(6,42) = 6.839$. The baseline condition was found to be significantly worse for lateral flight path control (132.63 feet). No statistical differences were found for lateral RMSE between the three tunnel concepts. No significant differences were found for vertical path error across the display concepts including the baseline condition ($p > .05$). Finally, no differences were found between the three guidance symbologies for RMSE.

Mental Workload

There was a significant effect found for tunnel with respect to workload, $F(4,28) = 43.40$. The baseline condition (4.167) was rated significantly higher in workload than the four tunnel concepts. The minimal tunnel (3.167) was also rated significantly higher in workload than the box (2.583), dynamic pathway (2.542), and dynamic "crow's feet" (2.417), which did not differ from each other. No significant differences were found for workload between the guidance concepts ($p > .05$).

Situation Awareness

There was a significant effect found for tunnel with respect to the combined SART ratings, $F(4,28) = 11.41$. The no tunnel, baseline condition (3.417) was rated significantly lower in situation awareness (SA) than the four tunnel conditions. In addition, the minimal tunnel concept (5.083) was rated significantly lower than the box (7.167), dynamic pathway (7.458), and dynamic "crows feet" (7.542) which did not differ from each other.

An ANOVA found a significant effect for tunnel, $F(4, 28)=84.369$ for the SA-SWORD paired comparison measure. Post hoc tests showed 4 distinct subgroups formed: 1) Dynamic; 2) Pathway; 3) Full and Minimum; and 4) Baseline. The dynamic crow's feet tunnel was ranked as having the greatest SA and Baseline (no tunnel) the worst. The ranking from highest SA to lowest was: Dynamic crow's feet tunnel, dynamic pathway tunnel, full tunnel, minimum tunnel and baseline (no tunnel).

For guidance symbology, an ANOVA found a significant main effect for SART, $F(2,14) = 5.33$. The ball was rated significantly lower in SA than either the tadpole or ghost, which were not significantly different from one another. The results from the SA-SWORD confirmed these results, $F(2,14) = 19.665$.

EXPERIMENT TWO

Experiment Two has similar objectives as Experiment One with the exception that the focus was on evaluating the efficacy of pathway concepts for a SVS head-up display. Other differences between the two experiments are described below

Pilot Participants

The participants for Experiment Two were similar to those used in Experiment One. All participants were 757-rated Captains who fly for Part 121 airlines and experienced with HUDs. The pilots were given extensive training before data collection began.

Experimental Tasks

The experimental tasks were identical to the tasks required of pilots in Experiment One including the "cut-the-corner" scenario, and each approach was flown to touchdown. Experiment Two also included a runway incursion scenario to evaluate "attention capture" for detecting other aircraft on the active runway (see Figure 2). The scenario involved a B-737 taxing beyond the hold line onto the active runway (note: circle added to Figure 2) whereas on other runs, the B-737 stopped before the hold line. Runway Incursion Prevention System (RIPS) technology and Traffic Collision & Avoidance System (TCAS) was inhibited during the approaches (i.e., TCAS fail). The order of the presentation of all scenarios and pathway concepts were randomly assigned.

Tunnel & Guidance Concepts

The tunnel concepts for Experiment Two were identical to Experiment One with the exception that the "box" and "dynamic pathway" tunnels were not included in the experimental matrix. Only the "minimal" and "dynamic crow's feet" were used because the results from Experiment One evinced that the box tunnel concept had too much clutter to be considered for a HUD. In addition, the "dynamic pathway" was similar to the "dynamic crow's feet" in terms of performance, situation awareness, and pilot preference for the PFD but many pilots thought there was too much clutter for a HUD. The "minimal" tunnel concept was included because it was hypothesized that clutter would be more of a concern for a SVS HUD than a PFD, and that the path deviation indicators and the pursuit guidance symbology may overcome the limited path information provided by the minimal tunnel.

Only the tadpole and ghost guidance symbologies were used in the present experiment because results from Experiment One indicated that the tadpole provided more information, with no added clutter, than that provided by the single integrated cue.

Simulation Facility

Experiment Two was conducted in the Integrated Flight Deck (IFD) fixed-based 757 full mission simulator. The IFD is designed to fully simulate the operational capabilities of a

B-757-200 with realistic out-the-window presentation. The synthetic vision display was a Flight Dynamics HGS4000 HUD with stroke symbology and raster synthetic terrain presentation.

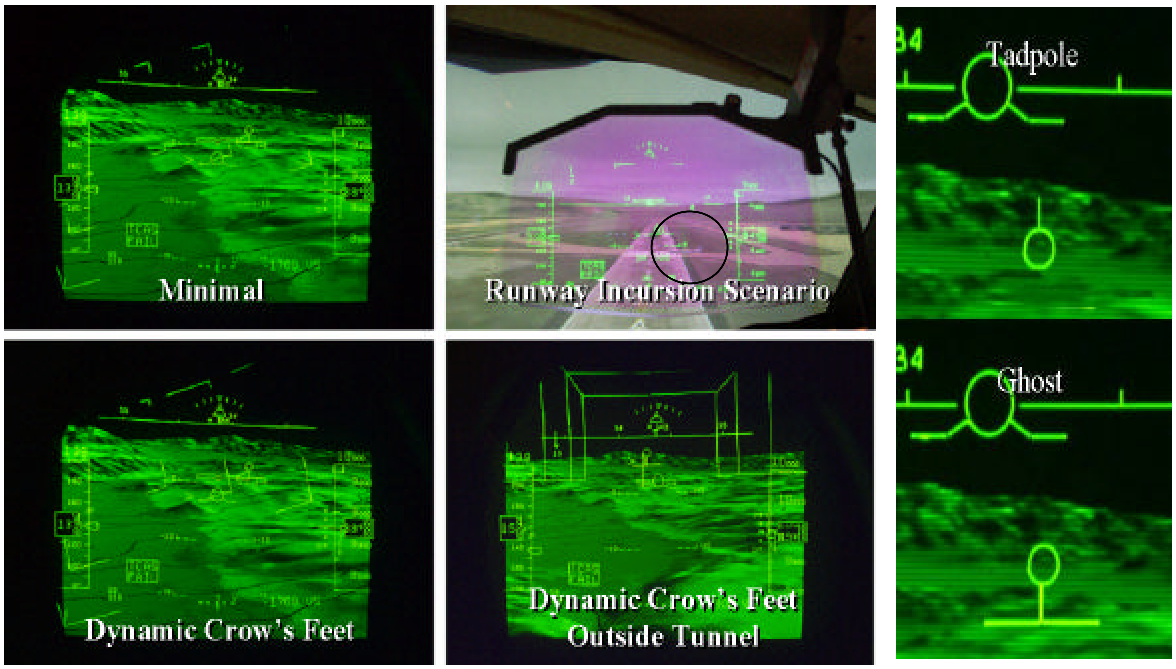

Figure 2. Synthetic Vision HUD Concepts and Runway Incursion Scenario

Results

After each run, pilots were administered a run questionnaire consisting of the USAF Revised Workload Estimation Scale, Situation Awareness Rating Technique (SART), and six Likert-type (7-point) questions specific to tunnel evaluation. A SA-SWORD and semi-structured interview were also administered. The post-run and semi-structured interview results are not discussed here, but support the results of the other dependent variables.

Path Performance

There were no significant differences among the tunnel concepts for either lateral or vertical root-mean squared error (RMSE) performance, $p > .05$. No significant differences were found for symbology or interactions ($p < .05$).

Situation Awareness

An ANOVA reported a significant difference for the SART across all concepts tested (i.e., guidance symbologies, $F(4,122) = 3.701$. A SNK post-hoc test revealed that the baseline was not significantly different from the dynamic crow's feet when flown with the same type of guidance symbology. However, the minimal tunnel concept was rated significantly higher than the baseline but not the dynamic crow's feet. There was also a significant difference found for tunnel concepts for the SA-SWORD measure, $F(2,16) = 17.81$. The dynamic crow's feet concept was significantly rated higher for situation awareness compared to either the minimal or the no tunnel concepts. The minimal tunnel concept was also a distinct subset and was significantly rated higher then the no tunnel concept. However, when paired with guidance symbology, the SNK post-hoc test revealed that the dynamic crow's feet with ghost symbology was significantly rated the highest in SA for both SART and SA-SWORD, and was significantly different than the no tunnel, tadpole and dynamic, tadpole concepts.

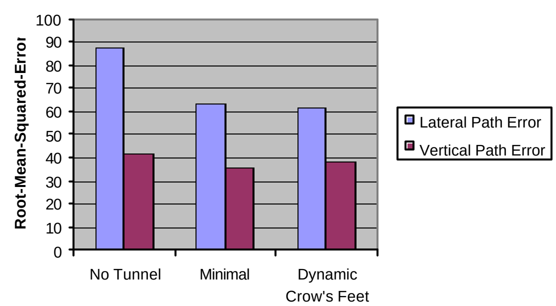

Figure 3. Root-Mean-Squared Error

Mental Workload

No significant differences were found for the revised workload estimation scale ratings for workload, $p > .05$. Overall, pilots rated the baseline concept to be slightly higher in workload (3.0/7.0) than the minimal tunnel (2.89/7.0) or dynamic "crow's feet" (2.72/7.0). A rating of "3.0" reflects "moderate activity" which is "easily managed". However, an ANOVA for the SWORD evinced two distinct subsets, $F(2,16) = 24.999$. The minimal and dynamic crow's feet concepts were not significantly different from one another in terms of workload, but both were rated lower than the no tunnel concept. No differences were found for guidance symbology or guidance x tunnel interaction ($p > .05$).

Runway Incursion Detection

Only one (1/9) of the commercial pilots failed to notice the transport aircraft on the active runway. During the post-experimental interview, he acknowledged that he saw the aircraft but it was too late to initiate the go-around and decided to land. The pilot felt that the situation did not pose any danger since he could land the aircraft further down the runway well beyond the incursion aircraft. Therefore, these results support that a HUD, even one with synthetic vision, does not significantly decrease unexpected event detection. However, to further safeguard against incursions, the NASA SVS concept will incorporate runway incursion prevention system (RIPS) technology (e.g., Jones, Quach, & Young, 2001).

DISCUSSION

Two experiments were conducted to examine the efficacy of different tunnel and guidance symbology concepts for head-down and head-up synthetic vision displays. The results indicated that the presence of a tunnel had a marginal effect on enhancing path control performance for the head-down display but not the HUD compared to the baseline (w/ guidance). However, there were significant differences in situation awareness and workload between both the head-down display and HUD SVS concepts. Experiment One found that the full or "box" tunnel concept was not acceptable because of clutter concerns. The minimal tunnel was also found to be poor for situation awareness compared to the dynamic tunnel concepts because it was difficult to accurately determine where you were in the tunnel. However, pilots did note that the presence of the guidance symbology and path deviation indicators significantly reduce this problem. Furthermore, all pilots felt that the minimal tunnel may be optimal for a HUD when issues of clutter are of particular concern compared to the PFD. The dynamic pathway was rated very high for SA, but several pilots reported that the presence of the tunnel floor ("railroad track") was unnecessary when compared to the dynamic crow's feet. For guidance symbology, the ball was found to be adequate but that the tadpole provided more information without an increase in clutter. The ghost, on the other hand, was the best overall for SA and workload because it gave yaw, pitch, and roll information.

Based on these results, the minimal and dynamic crow's feet tunnels and tadpole and ghost symbologies were examined in Experiment Two using a SVS HUD. The results were similar to Experiment One with one interesting exception. No differences were found between the tunnel concepts for SA. In fact, when the dynamic tunnel was paired with the tadpole, the minimal tunnel concept was rated significantly higher. It was only when the ghost was present was the dynamic tunnel concept found to provide the same level of SA as the minimal tunnel concept. Therefore, these results suggest that considerations of tunnel format and guidance symbology interact with type of SVS display. This is particularly important when synthetic vision may be presented on both a PFD and HUD because of the need to have the same tunnel and guidance symbology on both displays. For the PFD, the issue of clutter is not of such concern as compared to a HUD because of the need of the pilot to be able to look through the combiner glass to see the outside world. It should be noted, however, that in this experiment we did not allow the pilots to "de-clutter" the HUD as would be a capability of any synthetic vision HUD. Overall, however, pilots ranked ordered the dynamic crow's feet tunnel concept to be their first choice for both the PFD and HUD. Research is currently being conducted at NASA Langley Research Center to enhance the dynamic tunnel with tactical and strategic display information to help realize 4D Required Navigation Performance capability.

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